PREGNANT WOMAN MODEL FOR ABSORBED FRACTION CALCULATIONS

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1. INTRODUCTION

The most radiation-sensitive segment of our population is the developing fetus, especially during early organogenesis when the mother is frequently unaware of the pregnancy. To evaluate the risk of exposure, health physicists must have reliable estimates of the fetal dose from all sources of radiation. One important source of fetal exposure is the exposure that may occur from radioactive material within maternal tissues. These sources are important because of the proximity of the fetus to the maternal organs.

This paper describes the models of Reference Woman that were developed to describe each month of pregnancy. The models take into account the growth of the fetus and uterine enlargement as well as the displacement of the maternal abdominal organs. These models have been used to calculate absorbed fractions for the fetus as a target and the gastrointestinal tract as a source of radiation. Absorbed fractions for twelve photon energies ranging from 10 keV to 4 MeV will be published elsewhere because of space limitations in these proceedings.

2. PRESENT MODELS

The Snyder and Fisher model of Reference Man (1,2) is the most widely used model for calculating absorbed fractions (3) when one organ is irradiating another. Although the model and its organs have the dimensions and weights of Reference Man, Snyder and Fisher had the foresight to include a nongravid uterus in the phantom's mathematical description. Until relatively recently, most calculations of fetal dose during early pregnancy simply used the absorbed fraction values available for Reference Man. As a first approximation, these results were useful but suffered because Reference Man is considerably larger than Reference Woman and because they apply only to the nongravid uterus.

Several years ago the authors designed a Reference Woman phantom (4) that has body dimensions and weights quite similar to the ICRP Reference Woman (5). Basically the nongravid female phantom is a reduced version of the Reference Man phantom. The pregnant phantom contains a uterus and fetus represented by a cone that enlarges and changes angle as the pregnancy progresses. Nine versions of the female phantom were designed to represent the nine months of pregnancy. Figure 1 shows the phantom for 3-, 6-, and 9-months. The nongravid phantom was used to calculate specific absorbed fractions for the fetus during early pregnancy (6). The phantoms representing the nine months of pregnancy were used to calculate absorbed fractions when a dynamic bladder was the source organ (4). The models could not be used to calculate the absorbed fractions to the fetus from other abdominal organs during late pregnancy because of the displacement of these organs as the fetus and uterus enlarge. The models described in this paper include the necessary repositioning of the maternal abdominal organs and also a slightly modified fetal-uterine model.

3. FEMALE PHANTOM DESIGN

The female phantom has a mass of 58 kg and a height of 164 cm. Dimensions of the female phantom are 0.94 times those of the 70-kg Reference Man phantom, $(58/70)^{1/3} = 0.94$. Except for a change in the angle of the uterus and the shape of the cone's vertex, the fetal-uterine model is as previously described (4). Models of the uterus beyond five months have a rounded "vertex" so that each model more nearly resembles the uterine shape that results from the usual head downward position of the fetus during this period. Using x, y, and z coordinates that have their origin at the base of the

elliptical cylinder representing the phantom's trunk, Fig. 2, we can mathematically describe the position of the various organs during pregnancy.

a. Three-month Pregnant Woman

In the model for the 3-month pregnant woman, the uterus is placed with the lowest generator of the cone horizontal. The cone's vertex has x, y and z coordinates of 0,-4.23,7.52. The mass of the uterus and its contents at 3 months is 0.8 kg, which would probably depress the bladder somewhat. At this stage the uterus barely causes a bulge in the abdominal wall, Fig. 1. We neglect this small bulge, but do place the point of the uterus that is farthest in the direction of the negative y-axis at y = -9.2; that is, it is covered only by the "skin" of the phantom. No rounding of the vertex of the cone is attempted at 3 months. When the uterus is positioned as described, the equations for the hemisphere are $x^2 + (y+3.2)^2 + (z-12.5457)^2 \leqq 36$ and $-0.84(y-4.506) + 0.55(z-7.52) \geqq 9.2$. (1)

The equations for the conical part are

$$0.84\sqrt{x^2 + (y-4.506)^2 + (z-7.52)^2} \leqq -0.84(y-4.506) + 0.55(z-7.52) \leqq 9.2. \quad (2)$$

When so positioned, the uterus does not intersect most of the maternal abdominal organs, the exceptions being the bladder, small intestine, ovaries, and ascending colon. The intersections with bladder, ovaries and ascending colon are relatively minor and easily corrected by simple relocation of the organs. Considerable modification of the equations describing the small intestine were required to eliminate its intersection with the uterus. In the nonpregnant model the small intestine is described by the following equations:

$$\begin{aligned} &x^2 + (y+2.572)^2 \leqq (10.62)^2, \\ &-4.5684 \leqq y \leqq 2.068, \\ &15.98 \leqq z \leqq 25.38. \end{aligned} \quad (3a)$$

This volume also includes the transverse colon and portions of the ascending and descending colon, but these lie entirely outside the intersection with the uterus. Although in the plane x=0, Fig. 3a, the small intestine region intersects the uterus, the intersection decreases as $|x|$ increases and finally vanishes for $|x|>4.9199$. To eliminate this intersection, we devised a transformation which operates only on the intersecting regions, shaded area in Fig. 3a. The intersecting portion for each x-plane from x=-4.9199 to x=4.9199 is revolved 90° about a line parallel to the x-axis through point K. Each vertical segment is then translated upward until it no longer intersects the uterus, Fig. 3b.

In the 3-month pregnant model, the equations for the small intestine remain the same as those in Eq. 3a if $x^2 + (y+3.2)^2 + (z-12.5457)^2 > 36$. If $x^2 + (y+3.2)^2 + (z-12.5457)^2 \leqq 36$, the coordinates of the final image point

(x', y', z') become:

$$\begin{aligned} &x' = x, \quad y' = 11.4116 - z, \\ &z' = 17.1141 + y + \sqrt{36 - x^2 - (y+3.2)^2}. \end{aligned} \quad (3b)$$

Because at 3 months the orientation of the fetus within the uterus is unpredictable, an average absorbed fraction for the entire volume contained with the uterine wall is calculated.

b. Six-month Pregnant Woman

The uterus and fetus at 6 months is intermediate between the models at 3 and 9 months. Because of the considerably larger uterus, the equations describing the abdominal organs required more modifications at 6 months than at 3 months.

c. Nine-month Pregnant Woman

The model for the uterus and its contents at 9 months has been slightly changed from that shown in Fig. 1. We have rounded off the vertex of the conical portion of the uterus because of the usual head downward position of

the fetus. Moreover, the axis of the uterus is placed at a smaller angle. When positioned as shown in Fig. 1, the top of the uterus is at about z=37. The diaphragm is at about z=40, leaving little space for the remaining abdominal organs. Because of the fixed location of the ribs, the trunk cannot expand outward above z=33. We therefore allowed the uterus to depress the bladder by having the lowest generator of the conical portion pass through the center of the bladder. The rounded portion of the lower end of the cone (the cervix) is kept relatively fixed.

The stomach in the 9-month phantom is rotated so that its lower portion lies along the upper surface of the uterus. The ascending colon and the transverse colon are made somewhat triangular in cross-section since they must fit into the space between the uterus and the skin. The left kidney is raised 5 cm and the right kidney 4 cm, Fig. 4. The adrenals have been redesigned so they do not extend into the lung region. The ovaries are also raised. We have relocated the small intestine into the available space between the upper part of the uterus and the spine.

4. RESULTS

The absorbed fractions at 3 months are generally within a factor of two of the absorbed fractions obtained earlier by reciprocity (6). At 6 months the absorbed fractions are intermediate between those at 3 months and at 9 months of pregnancy. At 9 months, the absorbed fractions from a source organ to the different portions of the uterus and its contents depend on the source organ. For example, when the source organ is the contents of the stomach, small intestine, or the upper large intestine, the absorbed fractions are greater for the upper portions of the uterus where the legs and lower trunk of the fetus would normally be located. When the source organ is the lower large intestine contents, the absorbed fractions for the lower portion of the uterus would be greater. For photons of different energies the detailed results would differ qualitatively. At lower energies the uterus considerably attenuates the photons while at higher energies the absorbed fractions are approximately the same for the various parts of the fetus.

References

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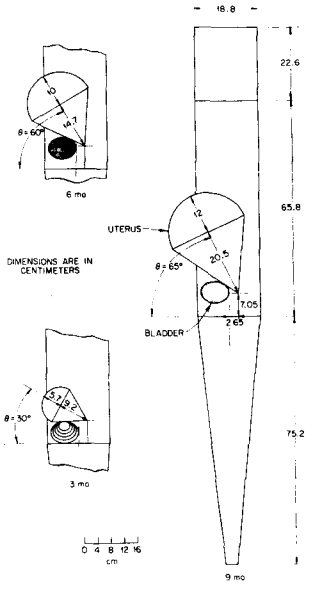

Fig. 1. Model of Pregnant Woman

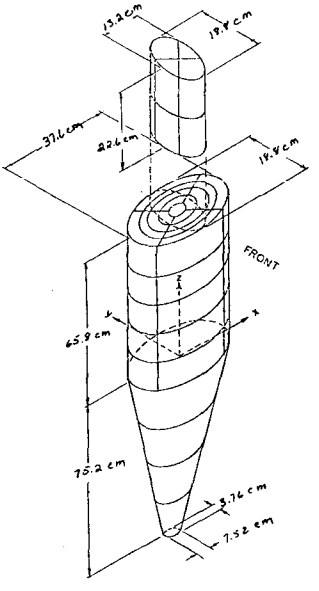

Fig. 2. Model of Reference Woman

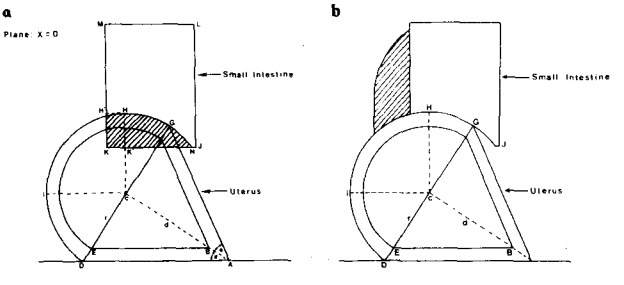

Fig. 3. (a) Model showing intersection of 3 mo. pregnant uterus and small intestine.
(b) Model of uterus and small intestine after transformation.

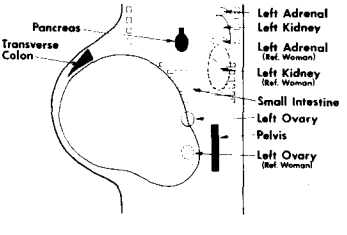

Fig. 4. Left sagittal view of abdomen of 9 mo. pregnant woman model. Dashed lines outline organ placement in nonpregnant model.